LEVEL II 12

# Hydraulic model study of a water intake under frazil ice conditions

*For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380,* Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: *Accumulation of frazil ice on unprotected intake model. (Photograph by J. Tantillo.)*

CRREL Report 81-3

# *Hydraulic model study of a water intake under frazil ice conditions*

Thomas J. Tantillo

March 1981

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS
By
UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) (14) CRREL-81-3

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: CRREL Report 81-3
2. GOVT ACCESSION NO.: AD-A099172
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): (6) HYDRAULIC MODEL STUDY OF A WATER INTAKE UNDER FRAZIL ICE CONDITIONS
5. TYPE OF REPORT & PERIOD COVERED:
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): (10) Thomas J. Tantillo
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: CWIS 31393
11. CONTROLLING OFFICE NAME AND ADDRESS: Directorate of Civil Works, Office of the Chief of Engineers, Washington, D.C. 20314
12. ~~REPORT DATE~~ (11) March 1981
13. NUMBER OF PAGES: 12
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 16
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
   - Frazil ice
   - Hydraulic models
   - Ice prevention
   - Water entry

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A 1:24 scale hydraulic model study of a water intake under frazil ice conditions is presented. The intake, located 9 m below the surface of the St. Lawrence River in Massena, New York, has a through flow of 0.14 $m^3/s$. The model study, conducted in the refrigerated flume facility of the U.S. Army Cold Regions Research and Engineering Laboratory, investigated methods of minimizing the frazil ice blockage on the intake. Two protective structures were modeled and the relative benefits of each are presented. The additional cross-sectional area provided by the protective structures lowered the vertical velocity component of the intake water to 0.0027 m/s. At this velocity the buoyant force acting on the frazil ice particle is larger than the downward drag force, causing the particle to rise. The results demonstrate that under certain low flow conditions a protective structure can minimize frazil ice blockage problems.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

037100

## PREFACE

This report was prepared by Thomas J. Tantillo, Mechanical Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, U. S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by Corps of Engineers Civil Works Project CWIS 31393, *Ice Effects on Energy Production.*

Darryl Calkins of CRREL and Dr. Samuel Lazier of Queens University technically reviewed the manuscript of this report.

# HYDRAULIC MODEL STUDY OF A WATER INTAKE UNDER FRAZIL ICE CONDITIONS

Thomas J. Tantillo

## INTRODUCTION

The Reynolds Aluminum Company operates a major aluminum reduction plant in Massena, New York. The facility receives its cooling water through two 0.76-m-diam. pipes which extend 107 m into the St. Lawrence River. These pipe inlets, located just downstream of the Snell Lock, are 30 m from the southern limit of the navigation channel (Fig. 1). Until a stable ice cover forms on the river upstream of the intakes, they are subject to frazil ice problems. In the past the frazil has blocked the intake entirely which severely curtailed the plant's operation. With the onset of winter navigation the stable ice cover has not been allowed to form, so that the intake has been felt to be subject to frequent frazil problems.

Frazil ice occurs when turbulent water, initially above 0°C, undergoes cooling at a rate of at least 0.01°C/hr (Giffen 1973, Granbois 1952). As the rate of water cooling increases, larger quantities of frazil ice are generated because of the greater supercooling.

The most common method of keeping trash racks on water intakes free of ice accumulation is by the application of heat. There is much disagreement in the literature as to what level of heat is necessary per unit area of trash rack, which can be explained by the varying water velocities and bar spacings of the intakes. Back flushing of water intakes has been tried at a number of installations with little success. More water is used to back flush the intakes than is taken in before the trash racks plug again. Other installations use traveling screens that are cleaned automatically or manually (Giffen 1973).

The purpose of this report is to present the results of tests on two protective structures that were modeled in a refrigerated flume to minimize the frazil blockage at the intake. The refrigerated flume as shown in Figure 2 is described in Appendix A.

The protective structures are basically concentric enclosures around the intake, which are open on the top and which set up a vertical velocity profile in the water entering the intake.

## MODELING CRITERIA

The active frazil disks produced in the flume are roughly of the same diameter as those generated in nature, approximately 2-3 mm. This presents a problem in model scaling because the frazil disks cannot be scaled down. To work around this non-scaling of the frazil disks, a kinematic model is proposed.

The kinematic model requires that the model and prototype have similar velocities, i.e.

$$V_p/V_m = V_r = 1 \qquad (1)$$

where $V_p$ and $V_m$ are prototype and model velocities respectively, with $V_r$ being their ratios. A suitable model scale for the intake structure was 1:24, or length ratio $L_r = 24$. This was chosen primarily by the constraints of the flume width and water depth. Since the internal velocities and frazil ice particle sizes are the same in model and prototype, the drag forces on the particles after they enter the structure are also equal.

### Dimensional analysis

The drag force $F_d$ on a frazil particle is a function of the water velocity $V$, particle size $d$, water density $\rho$ and water viscosity $\mu$:

$$F_d = \phi(V, d, \rho, \mu). \qquad (2)$$

Using the dimensional equation

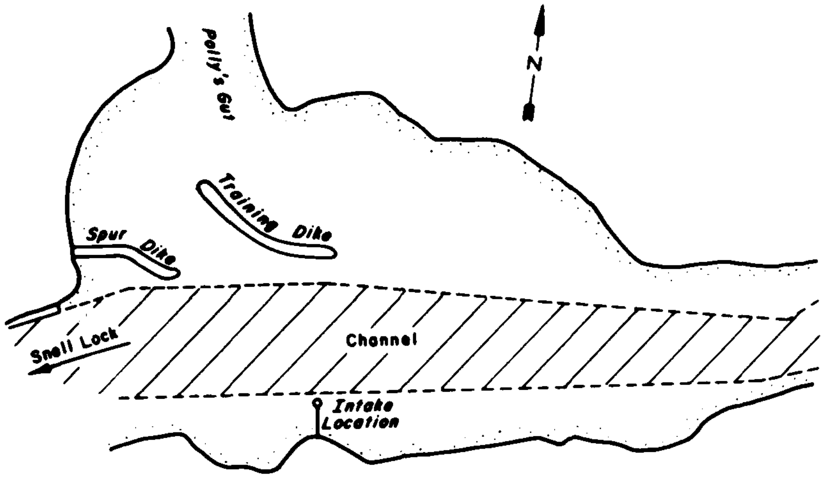


*Figure 1. Location of Reynolds Aluminum Company water intake on St. Lawrence River.*

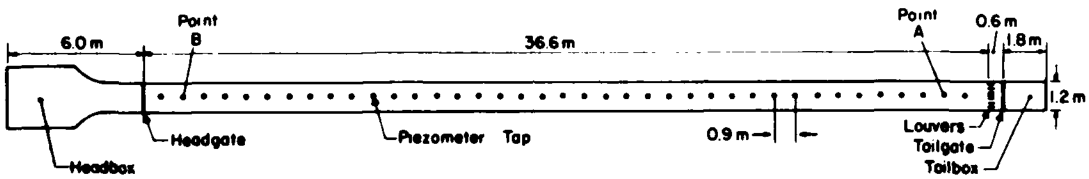


*Figure 2. Flume configuration*

$$F_d = K\, V^A d^B \rho^C \mu^D \tag{3}$$

eq 3 can be dimensionally related as

$$F = (LT^{-1})^A\ (L)^B\ (FT^2L^{-4})^C\ (FTL^{-2})^D \tag{4}$$

where force is $F$, length $L$, and time $T$.

Solving the above by use of the $\pi$ theorem results in

$$F_d = K\,[\,V^2 d^2 \rho\,(\mu/\rho V d)^D\,] \tag{5}$$

This yields $F_d/\rho V^2 d^2 = f(R_e)$ where the Reynolds number $R_e$ is equal to $\rho V d/\mu$. This $f(R_e)$ can be defined as the drag coefficient $C_d$, and White (1974) gives an empirical equation for the drag coefficient on a spherical particle as

$$C_d = 24/R_e + 6/(1 + \sqrt{R_e}) + 0.4. \tag{6}$$

Work done by Oseen (White 1974) shows that a disk normal to the free stream has a drag coefficient 0.85 times that of a sphere with the same diameter and low $R_e$.

A computer program was written to determine the downward vertical velocity at which frazil disks become neutrally buoyant. This velocity will occur when the drag force on the disk equals the buoyant force on the disk. If the downward velocity component is low enough, the buoyant force will overcome the drag force and the disk will rise. The variables are the downward vertical water velocity $V_v$, frazil disk diameter $d$, and thickness of frazil disk (typically $d/20$). The results are shown in Figure 3. For a drag force to buoyant force ratio ($F_d/F_b$) less than 1, the disk will rise.

For frazil disks of 3 mm, a limiting vertical velocity of 1.2 cm/s is reached and any higher velocity will result in frazil being entrained into the flow and into the intake.

From eq 1 the water discharge scale through the intakes $Q_r$ is thus

$$Q_r = V_r A_r = L_r^{\,2} \tag{7}$$

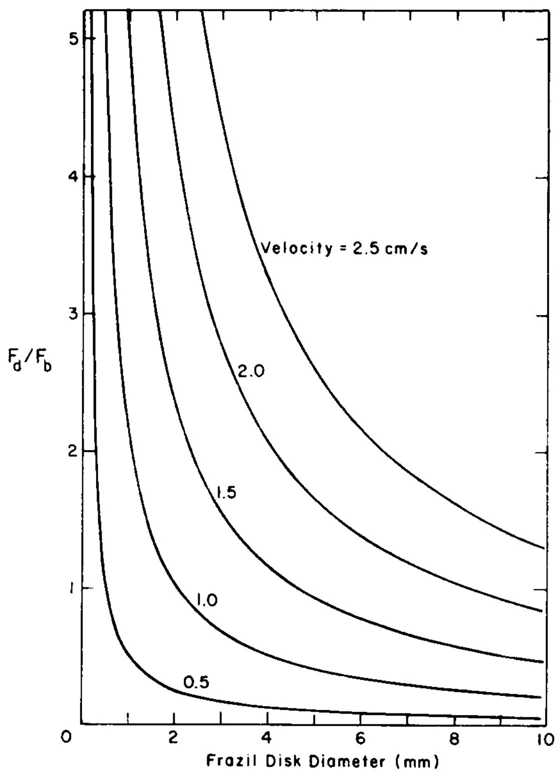


*Figure 3. Drag force/buoyant force ratio vs. disk diameter.*

with the time ratio $T_r$ merely

$$T_r = L_r / V_r = L_r \tag{8}$$

since $V_r = 1$ by definition.

Flow patterns around the structure are primarily the result of inertial and gravitational forces. The Froude number, which indicates the relative magnitude of the inertial to gravitational forces, is therefore the dimensionless parameter to be used for the free stream flow. The Froude number is defined as

$$F_m = V / \sqrt{gL} = F_p \tag{9}$$

where $g$ is the gravitational constant. The Froude numbers of the model $F_m$ and prototype $F_p$ should be equal to ensure similarity for the free stream flow. The free stream velocity criterion for similarity therefore is

$$V_r = \sqrt{L_r} \tag{10}$$

The Saint Lawrence Seaway Development Corporation (Adams 1977) obtained current direction and velocities by using drogues in the South Cornwall Channel in the vicinity of the Reynolds Aluminum water intake. The drogue measurements were made on 15 and 20 July 1977 with flows of 7050 and 7160 $m^3/s$ respectively. The results show that the mean velocity over the intake is between 0.12 and 0.30 m/s. The average value of 0.21 m/s was used for this study. The model free stream velocity was therefore 0.04 m/s for a 1:24 scale.

The model and prototype scaling parameters are shown in Table 1 using the two scaling criteria.

**Table 1. Scaling results**

| | *Model* | *Prototype* | *Prototype/ Model* |
|---|---|---|---|
| Intake flow | 245.8 $cm^3/s$ | 0.142 $m^3/s$ | $(L_r)^2$ |
| Intake velocity (cm/s) | 6.06 | 6.06 | 1 |
| Frazil disks (mm) | 2-3 | 2-3 | 1 |
| Intake accumulation time | 1 | 24 | $L_r$ |
| Free stream velocity (m/s) | 0.043 | 0.21 | $(L_r)^{1/2}$ |
| Structural scale | 1 | 24 | $L_r$ |

**Model of existing intake**

A 1:24 geometric scale model of the water intake was constructed using copper tubing for the inlet pipe and copper sheet for the conical sections and baffles as shown in Figure 4. The model was constructed from prototype drawings supplied by Reynolds Aluminum . The 1.83-m-diam. prototype intake is depicted in Figure 5. The model was placed in the center of the flume approximately 2 m from the tailbox.

The model intake piping system was calibrated for flow vs differential pressure head in the piping. Manual observation of a manometer recorded the changes in flow with time.

## TEST PROCEDURES

The scaled intake was placed in the flume (see Fig. 6), the scaled intake flow $Q_0$ was set at 245.8 $cm^3/s$. and a water depth of 35.6 cm was established. Frazil ice generation was initiated and time vs intake water flow was recorded manually (Tantillo 1979). This

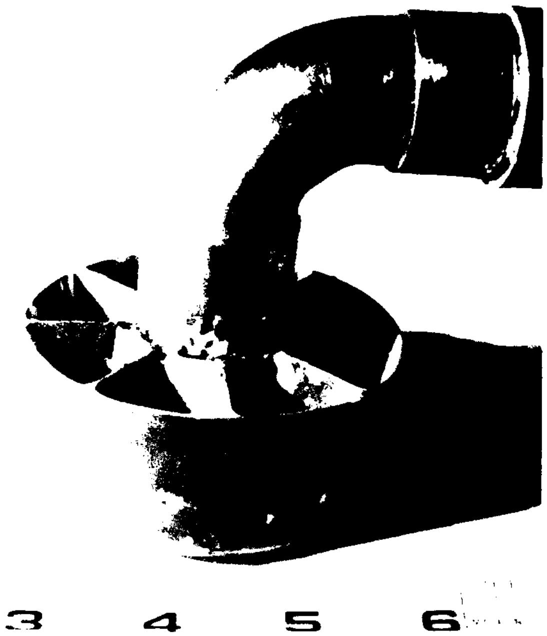


*Figure 4. Geometric scale model of intake.*

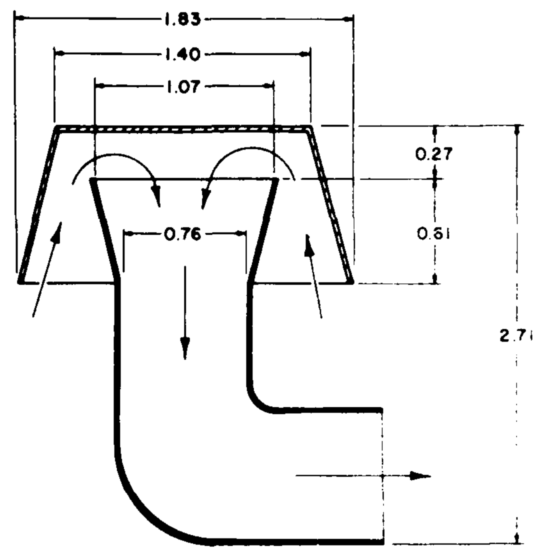


*Figure 5. Section of intake structure.*

procedure was repeated with two different intake protective structures (one circular and the other square) and each case was repeated at least five times. The test duration was limited to one hour due to frazil plugging in the flume tailbox.

With the velocities equal in the model and prototype structures, the prototype Reynolds number is 24 times as large as that of the model. The developing velocity profile would therefore be different. However, since the protective structure is less than half a pipe diameter in length, the profile in both cases is far from being fully developed with the majority of the structure area having the core velocity with a small boundary layer near the diameter. The result would be a slightly lower centerline velocity in the prototype than in the model, resulting from a decreased boundary layer thickness in the prototype due to the higher Reynolds number (Rohsenow and Choi 1961, Schlicting 1955).

Using the Froude criterion for scaling the free stream velocity, the $R_e$ of the model is 6200 whereas that of the prototype is 960,000. For the round protective structure flow separation in the prototype would take place farther downstream than in the model. For the square structure the separation would occur similarly at the corners. The results of this would be less of a wake in the prototype round structure due to reduced flow separation, and similar wake geometry for the square structure in the model and the prototype (White 1974, Schlicting 1955).

## TEST RESULTS

The unprotected intake structure became plugged quite rapidly with frazil as indicated in Figure 7. The average time was 17.2 min or 6 hr 53 min prototype time. As the accumulation of ice increases in the intake, the intake flow decreases due to the increasing head loss from the blockage.

A 34.3-cm-diam. × 20.3-cm-high circular protective structure which was open on the top was placed concentrically around the intake (Fig. 8). Using the open cross-sectional area the initial average downward velocity was calculated to be 0.0027 m/s. This structure decreased the accumulation rate as shown in Figure 9. It was observed, however, that this configuration allowed a recirculating vertical eddy to develop. This nonuniform flow field which developed in the structure allowed frazil to be entrained in the higher velocity regions, bringing it down to the intake and allowing accumulation to occur.

A 30.5-cm-square structure (20.3 cm high) having a 5-cm 45° lip was tested (Fig. 10) and gave an initial average downward velocity of 0.0027 m/s. An eddy still developed but it was reduced in intensity so that lower quantities of frazil were entrained. The rate of accumulation on the intake for this structure is indicated in Figure 11. After 30 min, which corresponds to 12 hours for the prototype, the amount of accumulation is reduced by an average of 50% from that of the round protective structure. This is due to

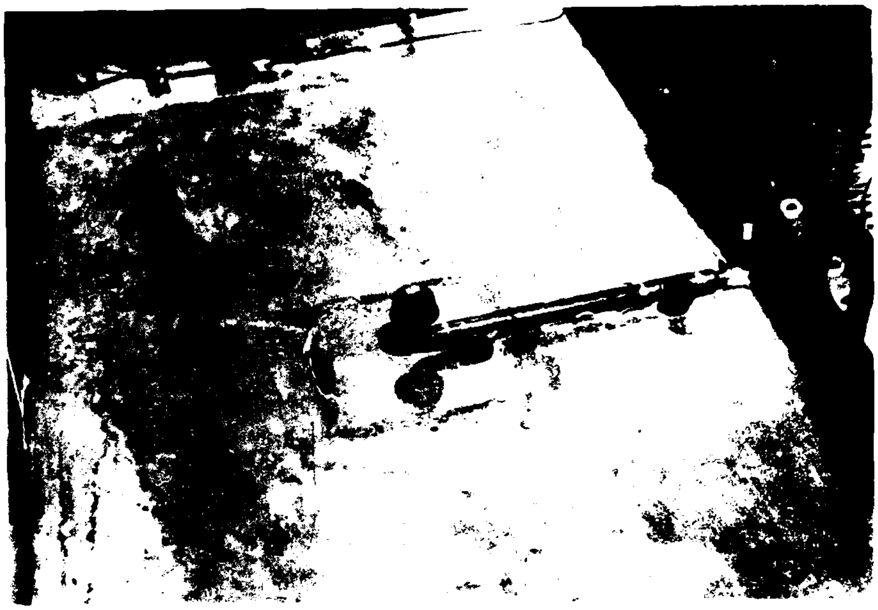

*Figure 6. Scale model of unprotected intake.*

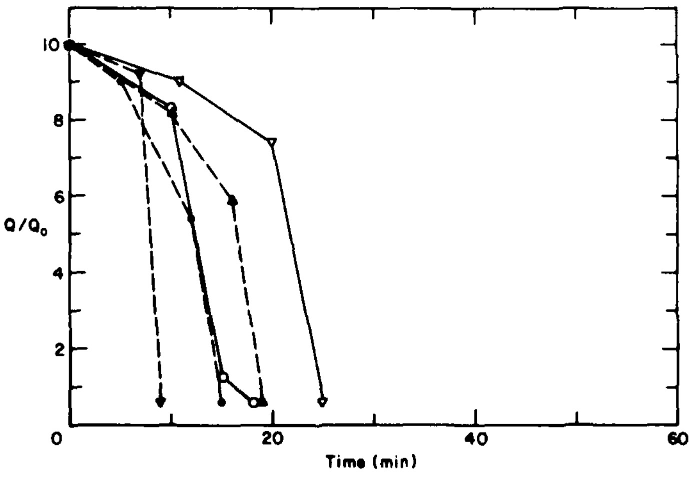


*Figure 7. Flow vs. time for unprotected intake.*

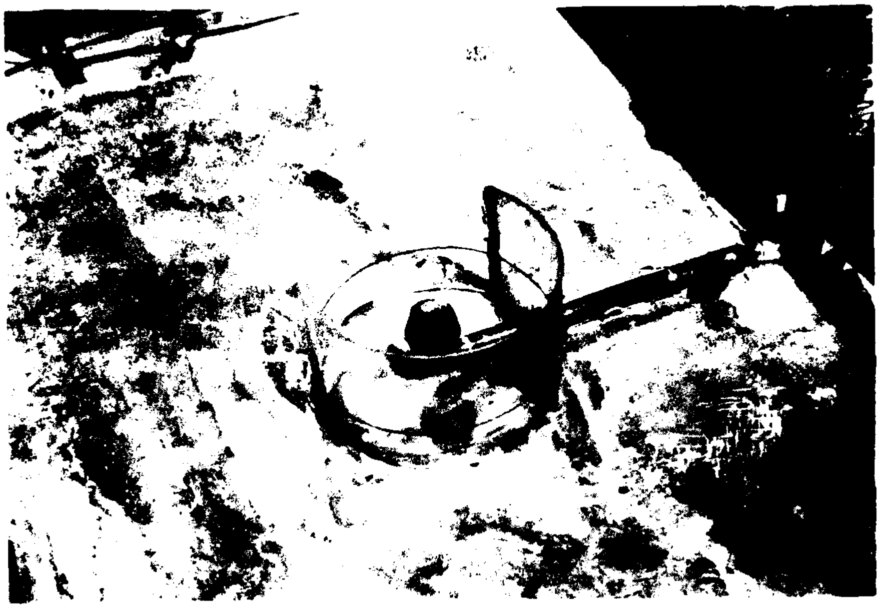

Figure 8. Round protective structure around intake.

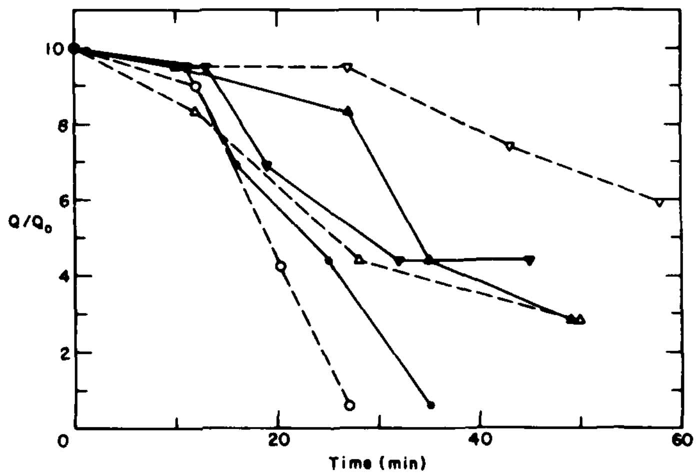


Figure 9. Flow vs. time for intake with round protective structure.

*Figure 10. Square protective structure around intake.*

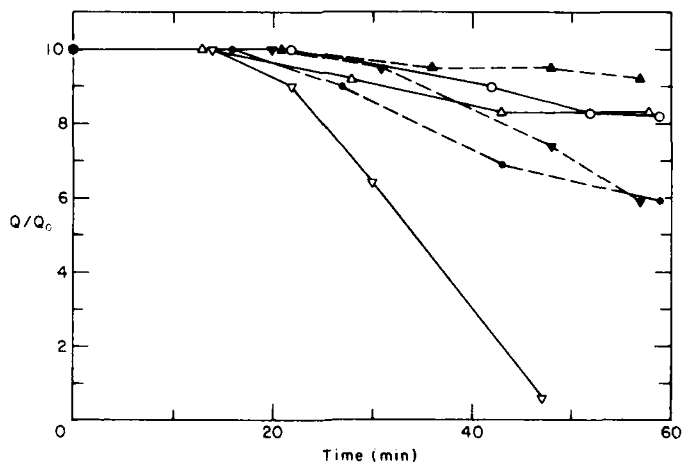


*Figure 11. Flow vs. time for intake with square protective structure.*

Figure 12. Accumulation of frazil ice on intake after 27 minutes with protective structure.

Figure 13. Accumulation of frazil ice after 25 minutes on unprotected intake.

the reduction of the eddy in the protective structure from the angled lip.

Typical accumulations of frazil ice are shown photographically in Figures 12 and 13. Comparison of Figures 12 and 13 shows the advantages of a protective structure.

## TEST LIMITATIONS

With the present flume configuration, it was not possible to obtain the correct Froude scaled depth and velocities and still generate frazil ice. The maximum depth at which frazil could be generated at the correctly scaled stream flow velocity was 0.875 of the calculated scaled depth. This resulted in larger recirculation patterns in the model protective structures than would be expected in the prototype, which enhanced the accumulation of frazil ice in the model. This makes the results conservative. The circulation patterns were checked at the correct scaled depth without frazil generation and it was observed that there were fewer recirculation eddies at this greater depth. This would reduce the amount of frazil being drawn to the intake.

With any water intake protective structure, there *must* be a minimum amount of recirculation in the downward direction. Recirculation will pull frazil ice into the intake and ultimately will result in blockage.

The modeling of frazil ice interactions with structures is still in its infancy. There is much yet to be learned.

## CONCLUSIONS AND RECOMMENDATIONS

A protective structure for a river bottom intake was designed which reduced the vertical water velocity to the intake enough so that the drag force of the entrained water flow on the frazil disk was overcome by the buoyant force of the frazil disk. A protective structure over the intake which created low vertical velocities was found to significantly increase the time before the intake plugged with frazil.

It is recommended that studies be carried one step further to arrive at a means of reducing frazil accumulation by using the waste heat in the discharge side of the water loop. This could be a more cost-effective and more reliable means of curtailing frazil accumulation.

## LITERATURE CITED


Adams, J. B. (1977) St. Lawrence River direction and velocity measurements. St. Lawrence Seaway Development Corp., Office of Engineering.

Griffin, A. V. (1973) The occurrence and prevention of frazil ice blockage at water supply intakes. Ministry of the Environment, Toronto, Ontario Research Branch Publication no. 243.

Granbois, K. J. (1952) *Combatting frazil ice in hydroelectric stations.* American Institute of Electrical Engineers Technical Paper 53-8.

Michel, B. (1971) *Winter regime of rivers and lakes.* CRREL Monograph III-B1a, AD 724121.

Rohsenow, W. M. and H. Choi (1961) *Heat, mass and momentum transfer.* Englewood Cliffs, N.J.: Prentice Hall.

Schlicting, H. (1955) *Boundary layer theory.* New York: Pergamon Press.

Tantillo, T.J. (1979) Frazil generation in a refrigerated flume. CRREL Internal Report 593 (unpublished).

White, F.M. (1974) *Viscous fluid flow.* New York: McGraw Hill.

## APPENDIX A: FLUME TEST FACILITY

The flume facility at CRREL (Fig. 2) is 36.6 m long, 1.2 m wide and 0.6 m deep. The flume has a slope range of -0.009 to 0.018 m/m. The system has two pumps that can circulate a total of 0.4 $m^3/s$, resulting in a velocity of 0.7 m/s at a depth of 0.46 m. This flow is measured with inline magnetic flow meters connected to flow controllers. The valves allow for automatic or manual flow control.

The underside of the flume bottom contains two refrigerated glycol loops, in seven- and six-channel paths, through which opposing or parallel glycol flows can be run in either direction. The glycol temperature can be adjusted between -18°C and 27°C.

The flume is situated in a room that can be refrigerated to -29°C. It has two zones of cooling, each with four air handling units, which are fed by a liquid ammonia refrigeration system. A refrigerated coil in the water storage tank can chill the test water to 0.3°C prior to testing.

A facsimile catalog card in Library of Congress MARC format is reproduced below.


Tantillo, Thomas J.

Hydraulic model study of a water intake under frazil ice conditions / by Thomas J. Tantillo. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1981.

ii, 12 p., illus.; 28 cm. ( CRREL Report 81-3. )

Prepared for Directorate of Civil Works, Office of the Chief of Engineers/by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory under CWIS 31393.

Bibliography: p. 9.

1. Frazil ice. 2. Hydraulic models. 3. Ice prevention. 4. Water entry. I. United States. Army. Corps of Engineers. II. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. III. Series: CRREL Report 81-3.